FOUR NEUTRINO OSCILLATION ANALYSIS OF ATMOSPHERIC NEUTRINO DATA AND APPLICATION TO LONG BASELINE EXPERIMENTS

OSAMU YASUDA

Department of Physics, Tokyo Metropolitan University
1-1 Minami-Osawa Hachioji, Tokyo 192-0397, Japan
E-mail: yasuda@phys.metro-u.ac.jp

Analyis of the Superkamiokande atmospheric neutrino data is presented in the framework of four neutrinos without imposing constraints of Big Bang Nucleosynthesis. Implications to long baseline experiments are briefly discussed.

1 Four neutrino analysis of atmospheric neutrinos

Four neutrino mixing schemes have caught much interest, since they are the simplest scenario which accounts for the solar and atmospheric neutrino problems and the LSND data[1] in the framework of neutrino oscillations. To reconcile the data at 90%CL of LSND, Bugey and CDHSW one has to have two degenerate massive states[2,3] ($m_1^2 \simeq m_2^2 \ll m_3^2 \simeq m_4^2$). For simplicity I assume $\Delta m_{21}^2 = \Delta m_\odot^2$, $\Delta m_{43}^2 = \Delta m_{\rm atm}^2$ and I adopt the notation in [2] for the 4×4 MNS matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}.$$

For the range of the Δm^2 suggested by the LSND data at 90%CL, which is given by 0.2 eV^2 $\lesssim \Delta m^2_{\rm LSND} \lesssim$ 2 eV^2 when combined with the data of Bugey E776 and KARMEN2, the constraint by the Bugey data gives $|U_{e3}|^2 + |U_{e4}|^2 \ll 1$. Also $|U_{s3}|^2 + |U_{s4}|^2$ has to be very small[2,4] if one demands that the number N_ν of effective neutrinos in Big Bang Nucleosynthesis (BBN) be less than four. In this case the solar neutrino deficit is explained by $\nu_e \leftrightarrow \nu_s$ oscillations with the Small Mixing Angle (SMA) MSW solution and the atmospheric neutrino anomaly is accounted for by $\nu_\mu \leftrightarrow \nu_\tau$. However, some people have given conservative estimate for N_ν and if their estimate is correct then $|U_{s3}|^2 + |U_{s4}|^2 \ll 1$ may no longer hold. Recently the Superkamiokande group has reported their result[5] on the solar neutrino experiment which indicates that the SMA and the Vacuum Oscillation solutions are disfavored. Meanwhile Giunti, Gonzalez-Garcia and Peña-Garay[6] have analyzed the solar neutrino data in the four neutrino scheme without BBN constraints. Their updated results show that the SMA solution exists for $0 \le c_s \lesssim 0.8$ ($c_s \equiv |U_{s1}|^2 + |U_{s2}|^2$), while the Large Mixing Angle (LMA) and LOW solutions survive only for $0 \le c_s \lesssim 0.4$ and $0 \le c_s \lesssim 0.2$, respectively. In this talk I will present some of the updated results of my work[7] on the four neutrino oscillation analysis of the Superkamiokande atmospheric neutrino data and I will briefly give some implications to long baseline experiments, assuming that the solar neutrino deficit is solved by the LMA solution. For details of the analysis and the references see [7]. In the analysis of atmospheric neutrinos, the effect of $\Delta m_\odot^2$ is negligible, so I assume $\Delta m_{21}^2 = 0$ and $U_{e3} = U_{e4} = 0$ for simplicity. To avoid contradiction with the CDHSW data, I will take Δm_{32}^2=0.3eV^2 as a reference value. The best fit to the atmospheric neutrino data[8] for 1144 days is obtained for $\Delta m_{43}^2 = 2.0 \times 10^{-3}$eV^2, $(\theta_{24}, \theta_{34}, \theta_{23}) = (45^\circ, -30^\circ, 20^\circ)$, $\delta_1 = 45^\circ$ and the allowed region at 90%CL is obtained

(The allowed region for 1144 day data is almost the same as for 990 day data). As a sample let me show the result for the case of $\theta_{24} = 45°,\ \delta_1 = 90°$. The shadowed area in Fig.1 (a) is the 90%CL allowed region projected on the $(\theta_{34},\ \theta_{23})$ plane for various values of Δm^2_{43}. If I demand that the solar neutrino deficit be solved by the LMA solution, then $c_s \lesssim 0.4$ which is depicted in Fig.1 (b). Combining the results on the atmospheric neutrinos and the solar neutrinos, the allowed region becomes the shadowed area in Fig.1 (c). It turns out that if I require $c_s \lesssim 0.4$ then the solution prefers relatively large θ_{23} for any value of δ_1.

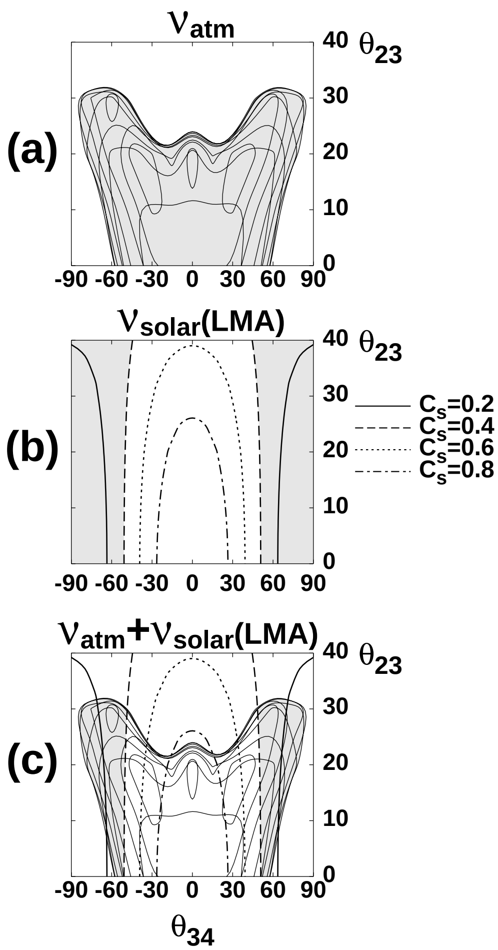

Figure 1. Allowed region for $\delta_1 = \pi/2$, $\theta_{24} = \pi/4$

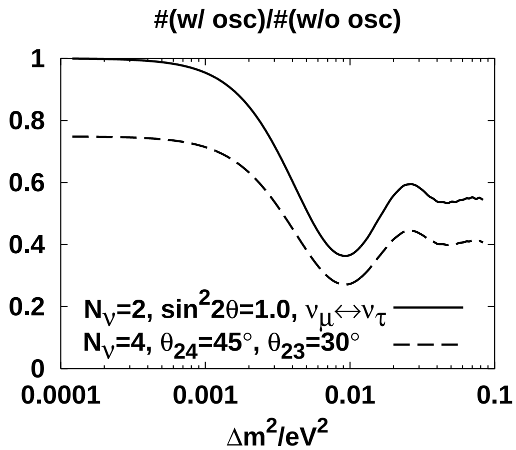

Figure 2. The ratio r at K2K

2 Application to long baseline experiments

First implication of the present scheme is the deficit which is expected to be seen at the K2K experiments. Ignoring the matter effect, I have for the neutrino energy $E \sim 1$GeV and the path length L=250km

$$P(\nu_\mu \to \nu_\mu) = 1 - 2|U_{\mu 2}|^2(1 - |U_{\mu 2}|^2) \\ -4|U_{\mu 3}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{\rm atm} L}{4E}\right), \quad (1)$$

where $|U_{\mu 2}| = |c_{24}s_{23}|$ is not necessarily small. The behavior of the ratio $r \equiv$#(CC + NC events with oscillations)/ #(CC + NC events without oscillations) as a function of $\Delta m^2_{\rm atm}$ is given in Fig.2. Because of the contribution of the first term on the RHS of (1) the ratio is lower for the present four neutrino scheme than for the standard two flavor case with the same $\Delta m^2_{\rm atm}$.

Second implication is the possible measurement of CP violation at the JHF experiment[9] which is expected to start from 2006. Since there is no strong constraint on the mixing angles θ_{24}, θ_{34}, θ_{23}, CP violation in the channel $\nu_\mu \to \nu_s$ could be large. If we measure the neutral current π^0 production for ν_μ and $\bar\nu_\mu$ beams and compare them[10],

Table 1. Yields of NC π^0 at JHF with 10^{21} POT

	no osc	$\delta_1 = \frac{\pi}{2}$	$\delta_1 = 0$	$\delta_1 = -\frac{\pi}{2}$
N_ν	393	357	311	282
$N_{\bar\nu}$	199	146	158	184

then the absolute value of the ratio

$$R \equiv \frac{\left.\frac{N_\nu(\delta_1)}{N_{\bar\nu}(\delta_1)}\right|_{\rm dat} - \left.\frac{N_\nu(\delta_1=0)}{N_{\bar\nu}(\delta_1=0)}\right|_{\rm MC}}{\left.\frac{N_\nu(\delta_1)}{N_{\bar\nu}(\delta_1)}\right|_{\rm dat} + \left.\frac{N_\nu(\delta_1=0)}{N_{\bar\nu}(\delta_1=0)}\right|_{\rm MC}}$$

could be significantly larger than the statistical fluctuation (~ 0.05 for 10^{21} POT) (The yields is given in Table 1 for an optimistic set of the oscillation parameters ($\delta_1 = 90°$, $\theta_{24} = 40°$, $\theta_{23} = 30°$, $\theta_{34} = 60°$, $\Delta m^2_{\rm atm} = 1.6 \times 10^{-3}{\rm eV}^2$). The ratio R is depicted in Fig.3 where the same set of the oscillation parameters as in Table 1 and the Wide Band Beam[9] is assumed in calculations).

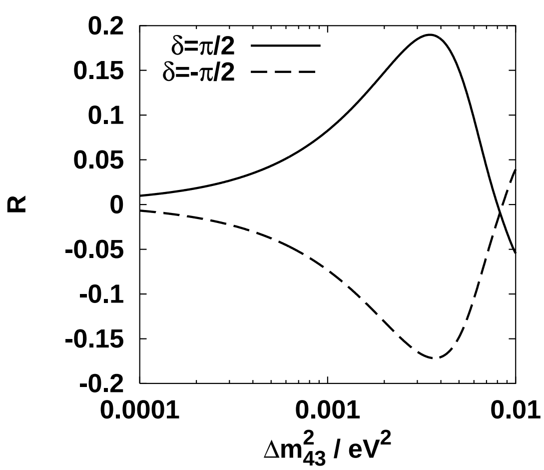

Figure 3. The ratio R at JHF

3 Conclusions

I have presented my result on the four neutrino oscillations of the Superkamiokande atmospheric neutrino data without assuming the BBN constraints. By combining the analysis on the solar neutrino data by Giunti et al. and assuming the LMA solar solution, I found that there is relatively large contribution of $\Delta m^2_{\rm LSND}$ in the atmospheric neutrino oscillations. It suggests that the number of events at K2K is less than the one for the standard two flavor scenario for the same $\Delta m^2_{\rm atm}$ and that CP violation could be measured at JHF after running for several years with 10^{21}POT/yr.

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